The dynamics of the Mediterranean Sea from space: some techniques and their applications

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THE DYNAMICS OF THE MEDITERRANEAN SEA FROM SPACE :

SOME TECHNIQUES AND THEIR APPLICATIONS

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ABSTRACT

This paper presents some remote sensing techniques and their applications to the understanding of the marine dynamics of the Mediterranean Sea. We emphasize the usefulness of the data provided by the meteorological satellites in the visible, near-infrared and infrared ranges.

Two techniques are discussed, the first dealing with estimations of wind magnitude at the sea surface, and the second with the prediction of the surface current field. Since the solar light reflected by the surface of the sea depends strongly on the sea state which is driven by the wind, observations of glitter pattern in the near infrared range allow measurements of the wind magnitude. On the other hand, estimations of surface current can be made either when considering patches observed in visible or infrared as passive tracers, or when solving the equation of the heat conservation using a couple of infrared images.

1. INTRODUCTION

Present day observationnal abilities from space permit the determination of surface and sub-surface fields which knowledge is of primary interest for the oceanographic community, and more generally for all the marine research community. For the Mediterranean Sea, accurate sea surface temperature (SST) fields are routinely recorded, maps of the distribution of the pigment contents in the upper layer are available, tides and internal waves have been interpreted in radar imagery from SEASAT (Alpers, Salusti, 1983), solar energy monthly received at the sea surface is currently estimated at fine scales from the METEOSAT data (Cano, 1982), assessments of large-scale water budget are possible (Guillard, Monget, 1983) as well as the long term monitoring of the oil pollution (Wald et al, 1984).

The amount of data coming from the meteorological satellites (polar orbiting or geostationnary) is huge and can only be handled by computer processing facilities.

Techniques whose degree of complexity depends upon the data, upon the goals one has to meet and upon the availale processing facilities, must be developped to extract the required informations from these data.

In this paper we discuss some image processing techniques we use in Ecole Nationale Supérieure des Mines de Paris in order to get information about the dynamics of the upper sea. Since the scientific aspects are presented elsewhere, they will only be mentionned here. These techniques are dealing with two different subjects, though both are related to the dynamics of the upper sea. First we will show how the wind magnitude can be estimated in a very simple manner from the sun glitter observed in the near infrared imagery. Then we will examine the prediction of the surface current field from visible and infrared data.

2. SEA SURFACE WINDS FROM SUN GLITTER OBSERVATIONS

Solar light reflected by the surface of the sea depends strongly on the sea-state which is driven by the wind. The surface of the ocean may be differentiated into small, mirrorlike facets that have individual characteristic slopes, each of which reflects according to the law of the reflection. At spacecraft altitude, the reflecting facets will not be individually resolved. Therefore the apparent radiance of the sea surface in any direction will depend on the fraction of the area having the proper slope for specular reflection. The observed pattern shows a radiance decreasing smoothly outward from its center, since greater and therefore less frequent slopes are required as the distance from the center increases. As the surface roughness increases with sea state, the pattern broadens and the level of radiance at the center decreases.

Thus either a measurement of the absolute radiance of the center of the glitter pattern or some suitable measurements of the pattern size will give an indication of the sea state and of the wind speed as well, since the broadening of the pattern is caused primarily by the capillary waves which are very sensitive to the local wind.

Recently, Wald and Monget (1983) presented a very simple method to retrieve wind speed from measurements of the broadening of the glitter pattern sensed by satellite. This method originated with an idea of Rozenberg and Mullamaa (1965), developped by Webber (1971), using the wave slope frequency distribution model of Cox and Munk (1954).

The frequency distribution of the occurence of wave slopes can be fitted to a first approximation by an isotropic bidimensional Gaussian distribution, whose variance is linearly related to the wind speed.

The method of these authors makes use of a portion of the glitter pattern image in order to relate relative radiance measurements within the pattern to the Cox and Munk statistics. In any point the wind speed is inferred on geometric grounds by the measurement of the distance between two isophotes surrounding this point. The wind direction is determined independantly by identifying the direction of the main axis of the glitter pattern ellipse.

In figure 1, is shown the glitter pattern obtained on July 23, 1979, 1411GMT. A wind speed of 6.5 m/s has been computed for location 39N ; 4E (south of Balearic Islands) while for location 45N ; 2W (Bay of Biscay) a wind speed of 3 m/s has been computed.

The wind speed can be derived at any number of locations, giving the knowledge of the wind magnitude field at synoptic scales.

Figure 2 shows a comparison between computed winds and winds derived from pressure charts, for 50 differents cases. The estimated speeds range from 0 to 17 m/s. The comparison shows very close agreement and demonstrates the success of this method. The standard deviation from the relationship drawn in figure 2 (full line) is equal to 0.5 m/s.

However this method suffers some restrictions : direction can be predicted with an ambiguity of 180° with a rms of 20° only if the wind is steady ; sunlight and cloud-free coverage are needed. When looking to the results, this method can hardly compare to the scatterometer of SEASAT, which was an all-weather sensor and gave estimates of wind speeds ranging from 0 to 24 m/s with a rms of 2 m/s and directions with an ambiguity of 180° with a rms of 20°. However the processing of SEASAT scatterometer data is more complex and a greater consumer of computer time than this simple method, with the result that the main advantages of our method are simplicity and scope of possible applications.

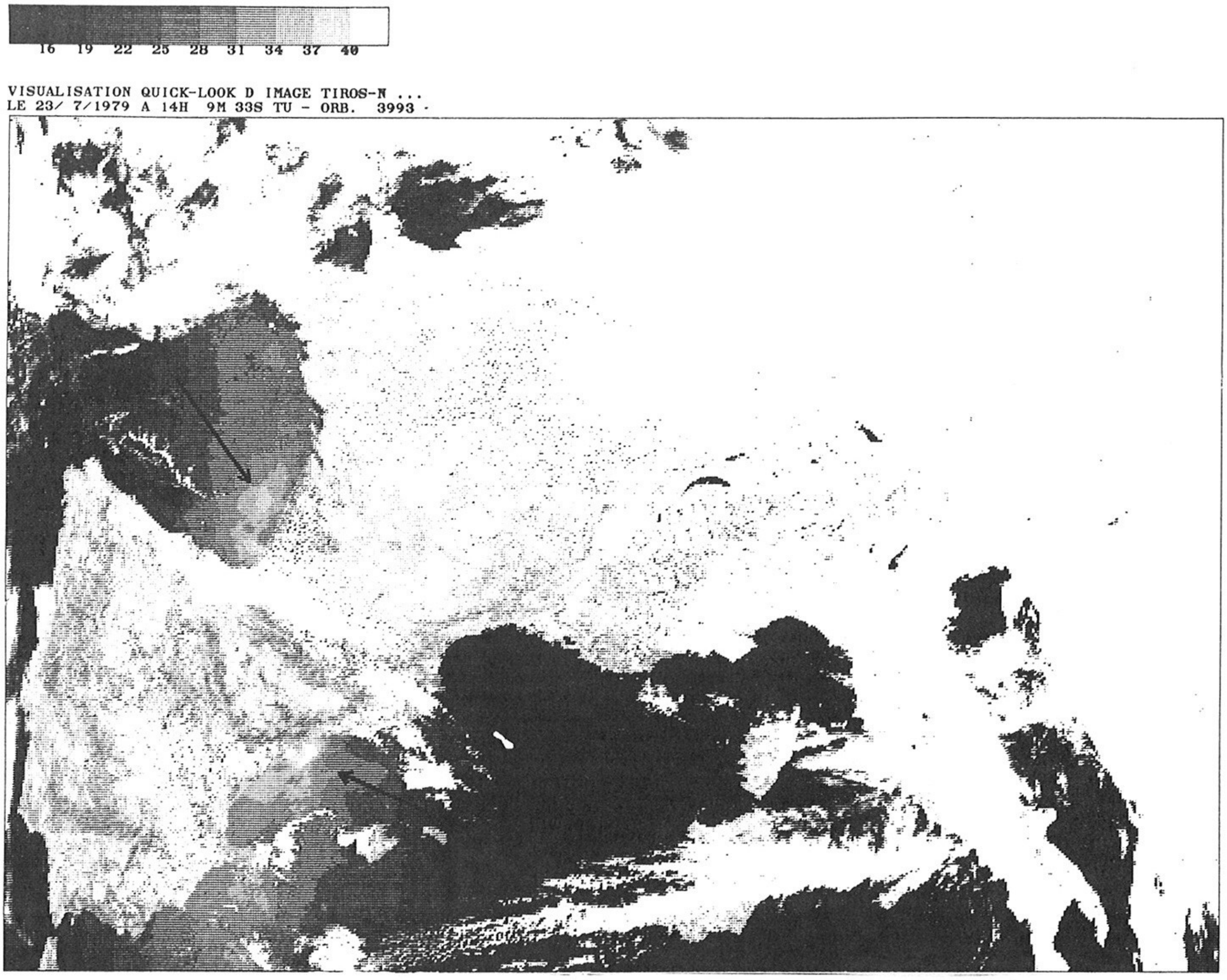


Fig. 1 Near infrared image obtained by TIROS N on 23 July

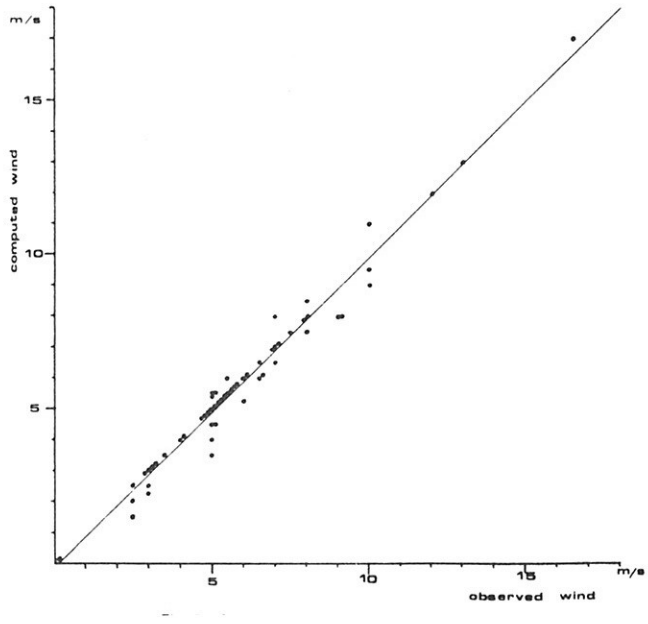


Fig. 2 Computed winds versus winds derived from pressure charts.

3. TRACING CURRENTS FROM SPACE

Since currents and their variability are the most important parameters we have to know to understand the ocean dynamics, oceanographers have always attempted to determine on an accurate basis the field of current at a synoptic scale and its evolution with time.

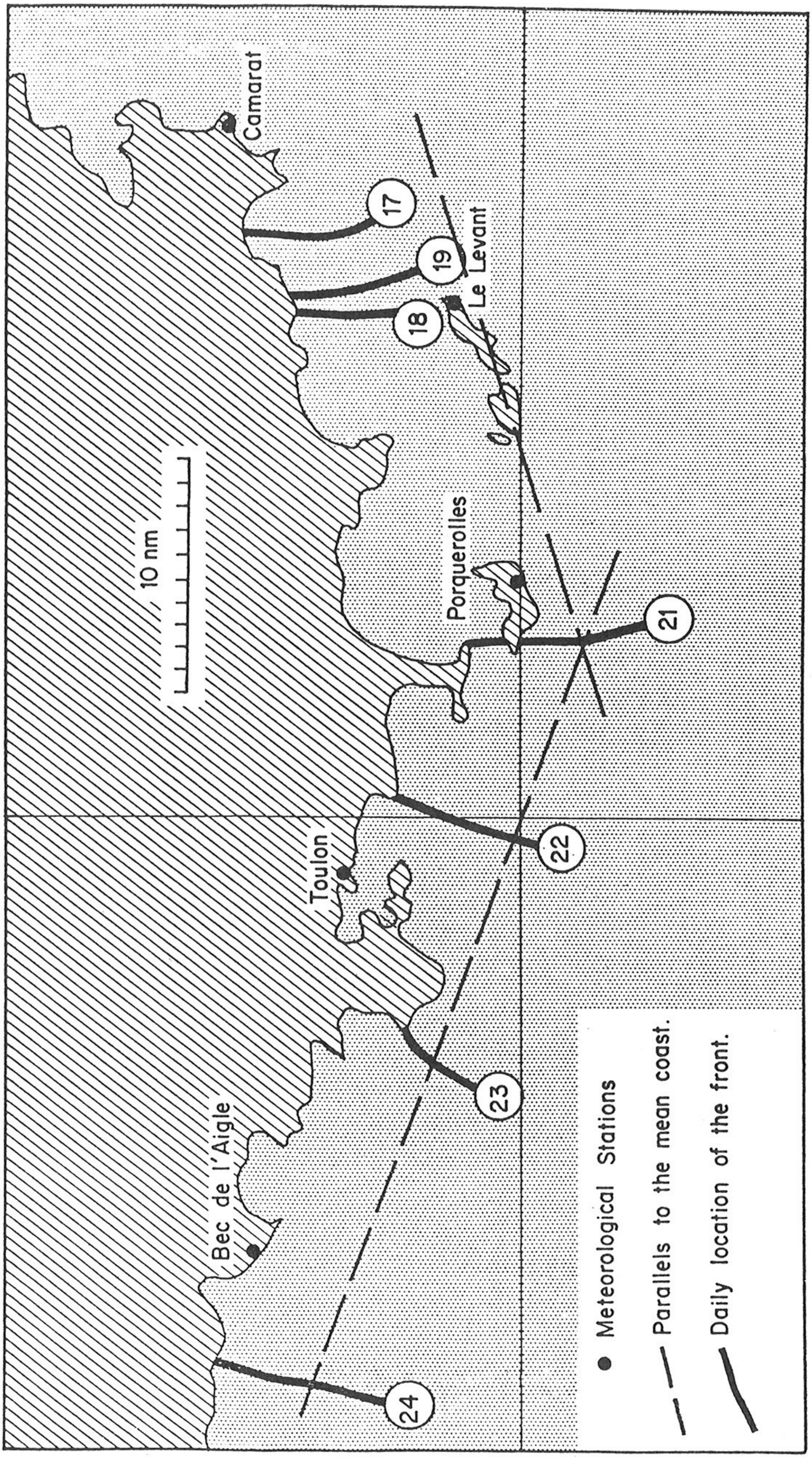
Methods have been used to measure surface current velocity from space. Thses include direct methods such as surface drifters tracked by satellite (Argos system) which gave very fruitfull results in recent campaigns in the Mediterranean sea.

Indirect methods such as satellite determined ocean topography have also been employed to diagnose the current field on longer time scales. However Bernard et al (1982) analyzing the SEASAT altimeter data over the western Mediterranean sea conclude that the satellite topography of the sea surface shows irregularities which are one order of magnitude greater than the expected oceanic effects, and so are mainly connected to the Earth structures.

We now discuss methods making use of the displacement of surface structures one can observe in time series of infrared or visible satellite images. Then in the following section, we present a method dealing with the equation for the heat conservation for a bidimensional movement. Using SST imagery time-series, this equation is solved numerically for the current field.

3.1 STRUCTURE DISPLACEMENT

Sometimes one can follow in consecutive images the displacement of one or more structures and can compute the velocity with which these structures move. When particularly applied to the visible imagery in which case structures are patches of suspended matter, Brown et al (1984) called this method the "Patch Motion Vector Method". It is the oceanic analog of the use of clouds as Lagrangian tracers of wind.


Camarat
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Toulon
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Bec de l'Aigle
24
Meteorological Stations
Parallels to the mean coast.
Daily location of the front.

FIGURE 3

Figure 3 shows an example of the determination of the flow speed from a satellite imagery time-series, after Millot and Wald (1980). These authors show that the surface part of the westward Ligurian current can be halted by strong opposite winds. Then a frontal structure with strong thermal gradients develops and represents the "head" of the current. As the wind stops, the surface water moves again, pushing the frontal structure westward. A record of the different locations of this front gives the speed of the current normal to the front, which is about 30 cm/s.

However some problems arise when using such a method.

The first obvious problem is to be sure that the structure one follows is the same in the whole time-series.

The second drawback is that only the velocity normal to the isolines can be estimated.

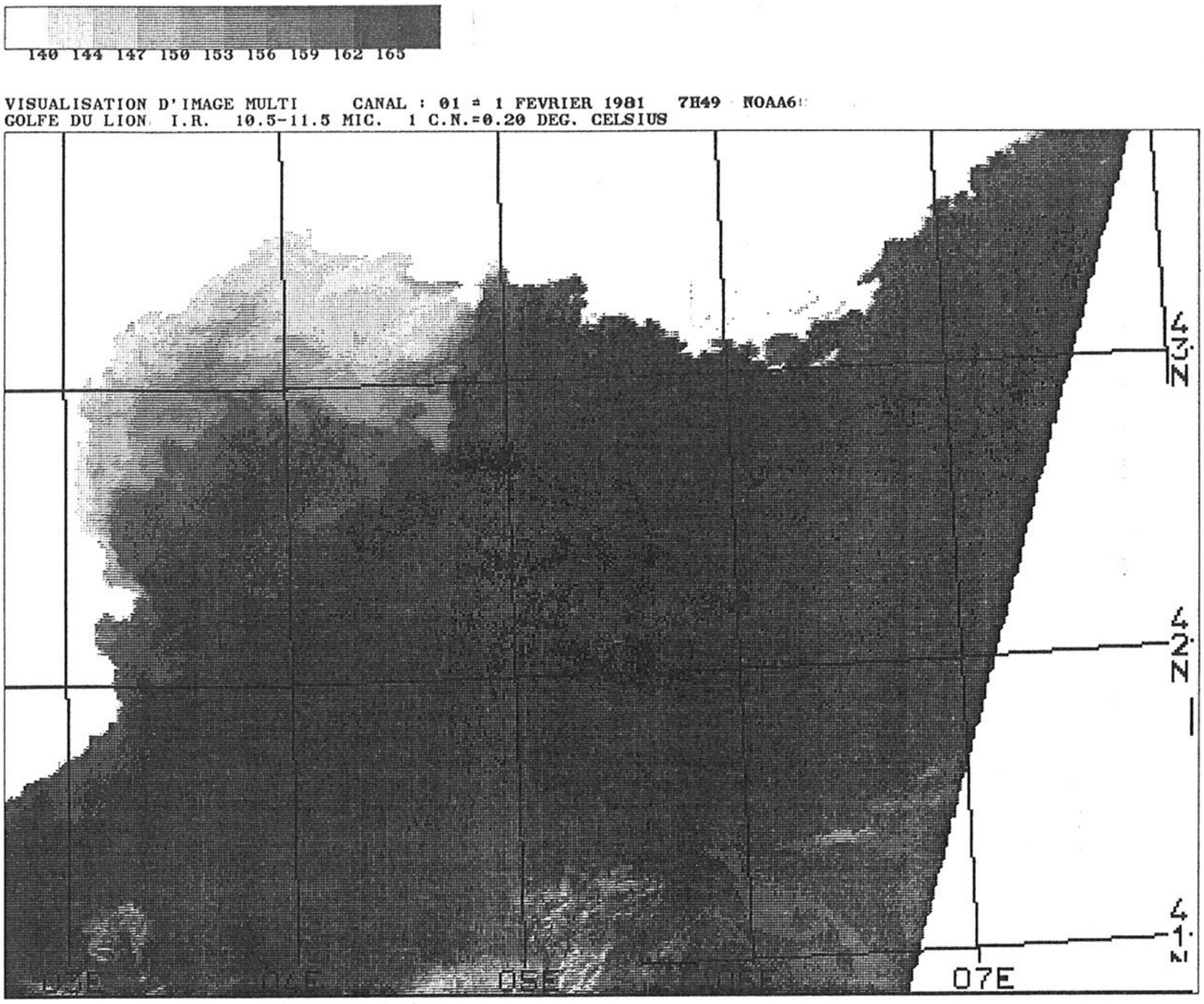
The third problem is to be sure that the estimated velocity is the speed of the current and not a phase velocity. Frequently one observes the displacement of a wave-like structure, as did for example Crépon et al (1982) in the Ligurian sea. Then the estimated quantity is the phase velocity, which can even be opposite to the mean current.

One also must be sure that the studied parameter is a good tracer of the current. It is not clear to which extent the structures seen in visible or infrared imagery can be linked to the flow structures.

In the Ligurian sea, a recent study shows a few structures revealed by measurements of nutrients, phytoplankton and suspended particulates which were unseen in hydrological measurements (Innamorati et al, 1983).

On the other hand, Gower et al (1980) interpret patterns on a LANDSAT image, south of Iceland, as being due to phytoplankton and show that their fluctuation spectrum is consistent with the phytoplankton distribution being controlled by advection in variable ocean currents, while being unaffected by their reproduction rates.

Figures 4 and 5 show an example of similarity between the thermal and color structures. Figure 4 display the SST field in the gulf of Lion as seen by NOAA 6, on February 1, 1981, at 0756 and 1919 GMT, while Figure 5 shows the same area seen by NIMBUS 7 in the blue channel for the same day, at 1055 GMT. The structures are more visible in the blue channel than they are in the IR image but they are similar in both spectral bands.



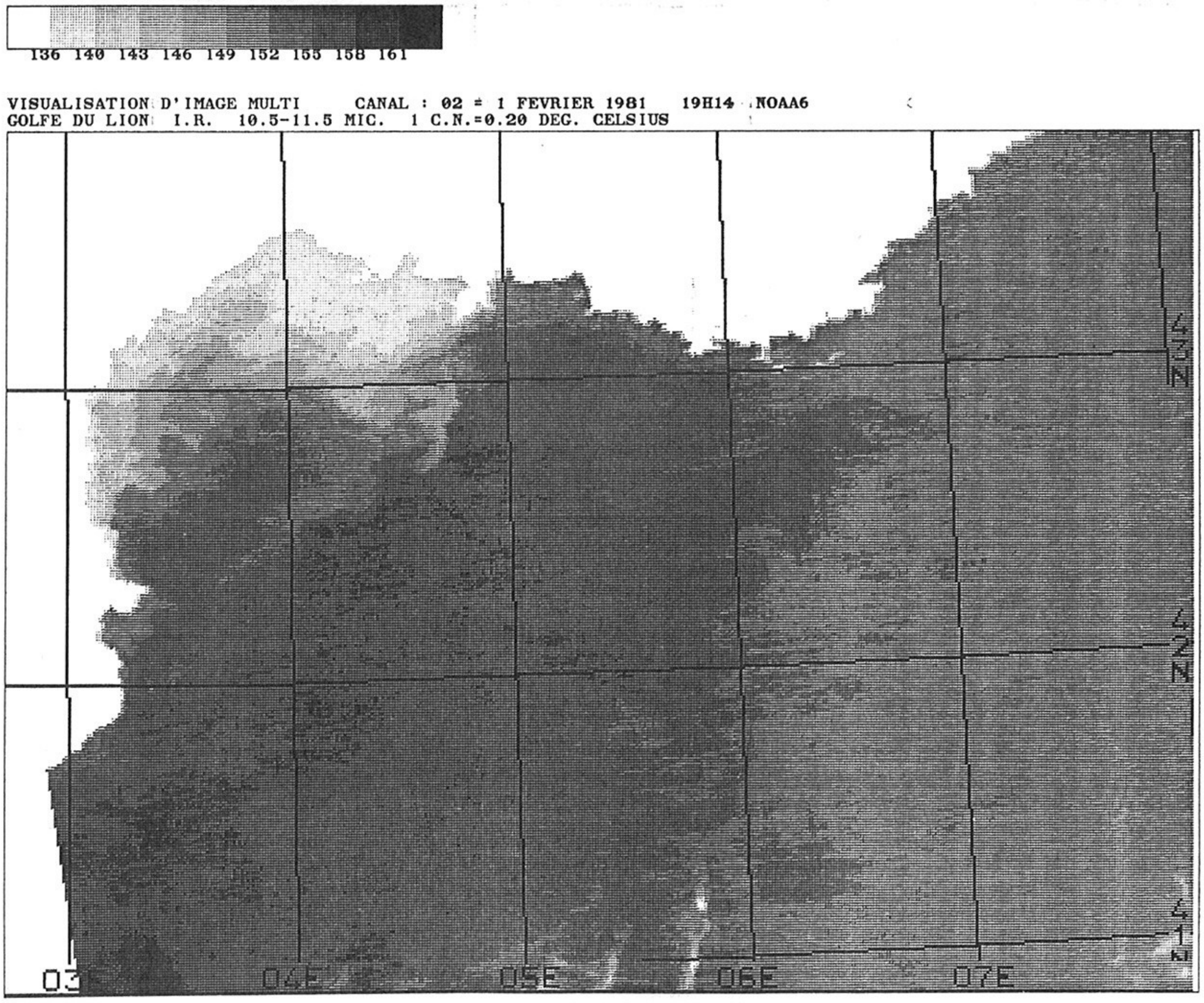


Fig. 4 Sea surface temperature pattern in the gulf of Lion, on 1 February, 1981, at 0756 GMT (fig. 4a) and at 1919 GMT (fig. 4b). The darker the tone, the warmer the temperature.

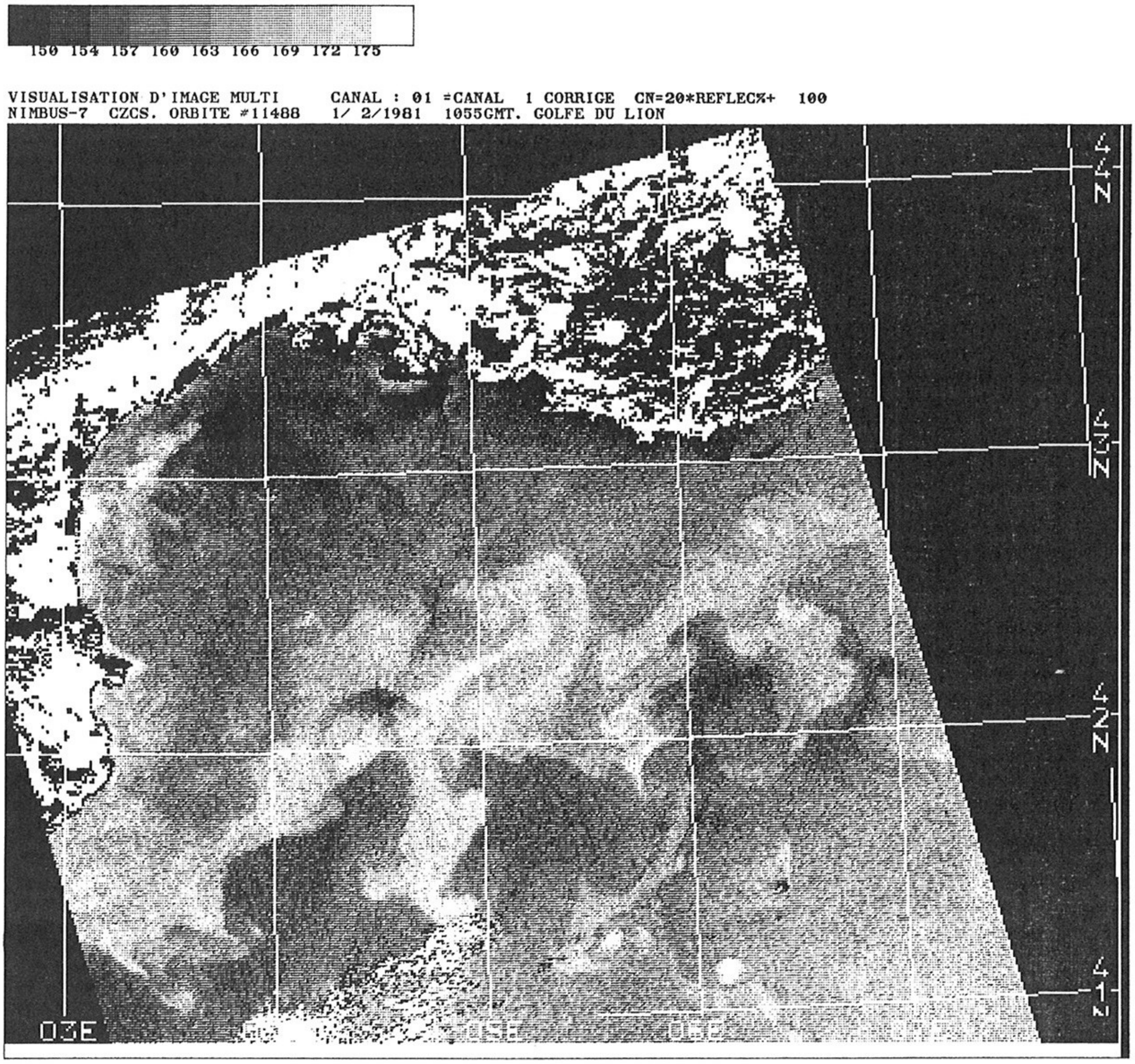


Fig. 5 Visible image of the gulf of Lion, observed in the blue channel by NIMBUS 7, on 1 February, 1981, at 1055 GMT. The darker the tone, the weaker the energy backscattered by the sea.

are There two fronts in this period. One is located alongshore in the western part of the gulf and can be seen clearly in visible and infrared imagery. This front has been documented by Champagne-Philippe and Harang (1982). The second front is offshore and is hardly seen in thermal imagery. It does not appear in the work of Champagne-Philippe and Harang because of the quasi-homogeneity of the SST in winter. However such structures suggest a strong unstable flow, which cannot be detected using infrared imagery alone.

This has been already underlined by Wald and Nihous (1980). They showed that the surface thermal pattern in the Ligurian sea in winter is uncorrelated with the circulation pattern since in this period, the main driving mechanism for the change in SST is the flow of cold air coming from the Alps.

The above examples show that one must be careful when interpreting a visible or infrared image as current structures. Also when particularly applied to visible, some works underline that both physical and biological processes, acting alone or together in a complex manner, can generate and maintain a plankton patch and that there is no evidence of necessary relationship between a plankton patch and the current field.

Plankton cannot be considered as a passive scalar being advected out by the variable ocean current. Plankton do grow and reproduce : a healthy population can double biomass in a time period of one day.

Haury et al (1978) quote that bological processes acting alone, such as predator-prey interactions and grazing, and interspecific competition for a common resource, can create pattern and that more generally reproductive and social factors act to generate and maintain a patch, even in a physically smooth world. Kahru (1981) discusses the diffusional instability of the ecological system. He postulates that the diffusion rates of each constituent of the system (nutrients, phyto- and zooplankton) are different, so that non-linear interactions may produce stable, steady nonuniformities of the concentration. Furthermore given the importance of vertical shear in the sea, Evans (1978) looks at the vertical movements of plankton and examines some of the possible patch-forming effects of these motions. One such effect is that the different vertical motions of nutrients and phytoplankton will lead to different shear-induced horizontal mixing rates, and hence possibly to diffusion-induced patches. Evans concludes that current vertical shear interacting with an ecosystem can generate plankton patches, even in a physically smooth world.

It results from the above cited works that the generation and the maintenance of a plankton patch can arise through physical and biological processes acting alone and/or together, and that there is no necessary link between the spatial patterns of plankton distribution and the current field.

3.2 MAPPING SURFACE FLOW WITH SEA SURFACE TEMPERATURE SATELLITE FIELDS

Assume a mean horizontal flow in the directions x and y, with no vertical current. Also assume that we can write for meso-scales that the short-term variations of the SST are due to horizontal advection and to the heating or cooling of the surface layer by turbulent exchanges with the atmosphere and the underlying ocean :

$$T_t + \vec{u} \cdot \vec{\nabla}_H T = Q \qquad (1)$$

where T is the SST, u is the current velocity, Q represents the temperature exchanges along the vertical axis, subscripts denote derivatives (t for time and H stands for horizontal). For this flow, a streamfunction ψ exists so that Eq. 1 becomes :

$$T_t - \psi_y T_x + \psi_x T_y = Q \qquad (2)$$

This equation is the starting point of the method. Given two consecutive SST fields obtained by satellite, one can compute for each pixel the time and space derivatives for temperature. Assuming that Q is known and also that the streamfunction is known in some points, the differential equation 2 may be used to compute the streamfunction field, from which the velocity can be derived.

A few initial values of the streamfunction are needed, in order to obtain an unique solution. This initial set of values can be given either by surface velocity measurements or by the coastline, which is a streamline. Then, the streamfunction will be determined all along the isotherms which intercept one of these initial points.

Such a method was described by Saunders (1973) and Vukovich (1974) but no comparison between their results and current measurements or even historical data was made. Recently, Wald, Brown and Olson (1984) used this method to derive the velocity field within a Gulf Stream warm core ring and find a reasonable agreement with coincident in-situ measurements.

During Spring of 1982, an extensive survey of a warm core ring and its surroundings was done by the Warm Core Ring Experiment Team. This ring is displayed in Fig. 6 (upper right), which presents the SST field as seen by NOAA 7, on 23 April, 1982. The shape of this eddy is more or less circular and measurements show that the surface velocities inside the ring are only a function of the distance from the center of the ring. A typical profile of velocity along a radius is presented in Fig. 7, in polar coordinates. Triangles are data obtained by a sonar-Doppler technique (APOC), while the full line results from hydrological data.

This profile was used to initialize the streamfield in the following way. Given a particular radius, the values of the streamfunction on this radius are those derived from this profile. Elsewhere the streamfield remains unknown.

After this initialization is done, the equation 2 is numerically solved for each point of the SST field. An example of the resulting streamfield is shown in figure 8. Then the velocities inside the ring are computed and compared to the in-situ measurements (full circles in fig. 7).

Four pairs of SST images were processed in that way and for each, the comparison between the computed velocities and the measured velocities shows a close agreement.

Fig. 6 Sea surface temperature on April 23, 1982. The darker the tone, the warmer the temperature. Note the Gulf Stream in the bottom (in the darkest tones) and the two rings north of it.

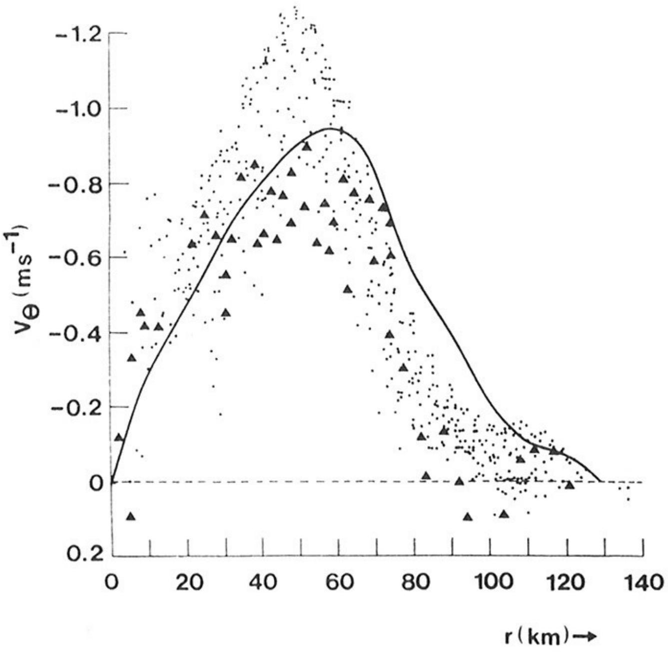


Fig. 7 Angular velocities versus the distance from the center of the ring (polar coordinates). Triangles are APOC data, full line results from hydrological data and circles come from the solver of Wald, Brown and Olson when applied to the SST images of 23 and 24, April, 1982

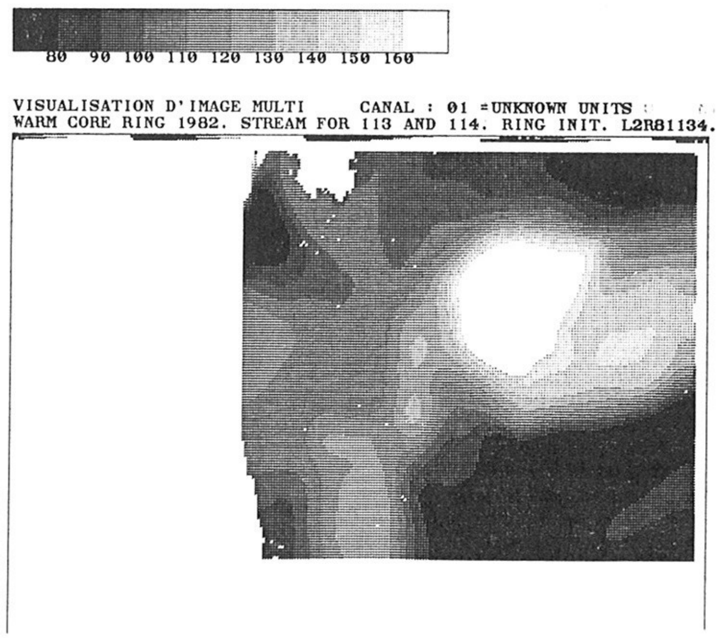


Fig. 8 Computed streamfield for 23 and 24 April, 1982. The flow leaves the lightest tones on its right (the whitest points or areas being uncomputed points or areas). Compare to the northernmost ring in figure 6.

4 CONCLUSION

We have presented two techniques using satellite data which can benefit the understanding of the marine dynamics of the Mediterranean sea.

The first one makes use of the near-infrared data which indicates the quantity of solar light reflected by the sea surface. By using a model of the frequency distribution of the very short waves slopes, which are very sensitive to the local wind, the wind speed can be estimated with a reasonable accuracy. Despite some restrictions, this method can be useful in some areas where no meteorological data are available.

With the second technique, the field velocity can be accurately derived from satellite measurements of the sea surface temperature. Two kinds of initializations are possible : coincident ship measurements or coastline. This solver has wide applications. For example, given a set of velocity measurements across the Gulf Stream in the Strait of Florida, the map of velocity inside the Gulf Stream can be derived for the whole stream and will be only interrupted by the presence of clouds.

The resulting product of this solver, a velocity field, is a very new one, never measured by the oceanographers on such scales. In our opinion, this method will benefit the actual studies on ocean dynamics but will likely rise new research goals which require the knowledge of the synoptic velocity field, such as the spatial variability of currents.

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